# Designing a Photovoltaic System Hybrid for a Health Clinic

## In Camilo Ortega, Nicaragua

## By


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# Acknowledgements

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# ABSTRACT

As developing nations continue to foster the development of their technologies and economies, industrialized nations have taken an active approach in providing green and sustainable alternatives for them to consider. Non-profit organizations like Engineers Without Borders holds sustainable international development as paramount to all international projects that their student and professional chapters undertake. The Cal Poly Engineers Without Borders student chapter has implemented a variety of projects from slow sand filters to compressed earth blocks, and the Nicaragua team is in the process of designing a health clinic for the Camilo Ortega community. In order to power the health clinic, the team has decided to consider solar power as the power application of choice.

This report will discuss the general set up of any hybrid-photovoltaic system, the climate of Nicaragua, the availability of photovoltaic system components in-country, the expected loads that the clinic will foresee, and the sizing for the photovoltaic array, battery array and generator back-up, and economic and environmental impact of these results.

# INTRODUCTION

A Photovoltaic (hereafter, PV) system is one which harnesses the sun's radiation of energized photons to generate electric current in a specific material. Silicon (single and multiple crystal) is often the most commercially available and selected choice in PV system installations. Like any energy source, there incurs a series of benefits and costs that one must take into account; solar irradiance in perspective region, required power, and available materials to name a few. A hybrid system means that the PV system will be backed up by a generator in the case that the PV array cannot provide the necessary amount of power to the battery array, due to issues such as poor irradiance due to extended cloud cover. A detailed schematic of the hybrid PV system can be seen below in Figure 1.

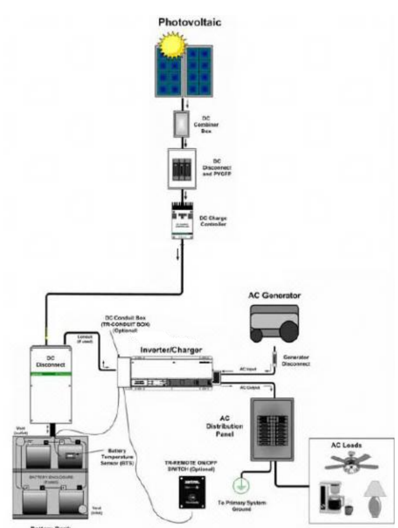


*Figure 1: Basic Schematic of the Hybrid Photovoltaic System*[1]

As can be in Figure 1, the schematic has certain essential components. For any PV system, there are requirements such as the PV array itself, a charge controller, charging system, a battery bank for storage, and an inverter for AC loads. Specifically for this design, the AC generator will allow the batteries to regenerate charge when they achieve a certain discharge point. Ideally, the AC generator will be used as little as possible for noise and pollution control, but it is necessary in the event the load is simply too high. For this project, I am focusing on these main components, but additional components for the PV system such as break boxes and fuses will become apparent as the project continues.

# BACKGROUND

Barrio Camilo Ortega is a community of about 19,000 people that live 15 miles southeast of the Managua, the capital of Nicaragua. This community consists mostly of women and children as Camilo Ortega originated as a refugee camp during the Sandanista revolution. The community also faces poverty and a lack of access to health care. Health care is centralized in the main capital of Managua which requires residents of Camilo Ortega to purchase a taxi ride to receive health care; an expense which many cannot afford let alone the health care expenses. Members of the community face many hardships including unsafe or unsanitary sites for giving birth, acute respiratory illnesses, and general lack of health checkups.

Engineers Without Borders – Cal Poly has a team working to fix this problem. As part of a 3 year project, the team is seeking to design, implement and construct a health care clinic in the heart of Camilo Ortega. In conjunction with the Non-Governmental Organization ATRAVES, the team hopes to complete the final construction of the clinic in the summer of 2010. Once that clinic is constructed, it is going to require power to run and provide adequate healthcare when needed. A majority of the power in Camilo Ortega is actually pirated off the main utility lines as a result the clinic must be powered through new and sustainable methods which is why a photovoltaic approach has been taken. For this reason, there are two choices for powering the clinic; a diesel generator or a renewable energy source. Running the health clinic solely on a generator would be a poor choice as gas prices rise to meet global demand. Another down side to the generator would be its consistent noise and air pollution that it would cause to this small community. With a renewable energy source, all of these things will cease to be a problem, but as this community does not run of the power grid, it will be essential to design a standalone hybrid PV system.

Luckily, for adequate and appropriate sizing of locally available solar materials, a local supplier has been found in the capital of Managua. ECAMI is a company that in addition to working for profit, works with international development organizations like Engineers Without Borders in order to implement sustainable technologies throughout Nicaragua. With an understanding of the kind of materials they have in their possession, it can make it infinitely easier to size the system appropriately.

# Requirements

In working with the Non-governmental Organization (hereafter, NGO) ATRAVES, we collaborated on the requirements, in terms of power, that would have to be supplied to fully provide enough power for all expected instruments, devices, lighting, and possible expansion.

Optimally, a photovoltaic system should provide *all* the power to the clinic to reduce pollution of noise and exhaust fumes, but it is understood that due to logistical or financial reasons, all requirements may not be met. Table 1 below lists requirements for the project, while Table 2 below lists the priorities of the system.

*Table I: Project Requirements*

| Requirements | |
|---|---|
| 1.0 | Understand the Climate and Irradiance of Managua, Nicaragua |
| 2.0 | Research and Size the Expected Loads of the Clinic |
| 3.0 | Research the Available Photovoltaic System Components |
| 4.0 | Appropriately Size the Photovoltaic Panels, Batteries and Back-up Generator |
| 5.0 | Understand the Cost of the Project and Research Possible Alternatives |

*Table II: Project Priority List*

| Priorities | |
|---|---|
| 1.0 | Keep Load at a Minimum by Understanding Options |
| 2.0 | Size All Systems to Ensure Power at Maximum Load |
| 3.0 | Photovoltaic System Sizing |
| | (Given Logistical or Financial Restraints) |
| 4.0 | Combination Sizing |
| 5.0 | Purely Diesel Generator Sizing |

As Table 2 shows, the ultimate priority of the system is to keep it clean, appropriate, and sustainable by providing merely a photovoltaic system. As will be discussed later, the initial cost of investment into a PV system is large and as a result comprises with the load or elsewhere must be made. Costs must be considered in *all* parts of this project.

## Photovoltaic System Requirements

The system must be able to fit on the roof of the clinic as ground space is limited, and alternate hazards such as vandalism or theft must also be considered.

The battery system must fit into a rather small room being sized in the clinic and it must be safe.

The initial system designed should provide 100% of the clinics power throughout the year (on battery support). Alternatives must provide at least 75% of the clinic power throughout the year.

## Alternatives and Diesel Generator System Requirements

Many of the same design requirements listed above apply here, but with the addition of the generator, an additional requirement must be met. Generators must be set-up for the minimal running time, or in the case of a generator only system, the generators must provide enough power for a limited load for prolonged periods of time. Another alternative, discussed later, must ensure that the battery bank can sustain power long enough to the clinic in the event of power outage or blackout.

# SYSTEM DESIGN

## CLIMATE AND IRRADIANCE

Nicaragua's climate is diverse as its terrain. On the eastern Caribbean coast, it rains for a large portion of the year and thus, implementing a photovoltaic system there could be a hearty task. Camilo Ortega, on the other hand, lies in the Pacific lowlands, but not directly on the Pacific coast.


*Figure 2: Map of Nicaragua with Managua Highlighted[2]*

As Figure 2 shows, the highlighted area shows the location of Managua—and by association—Camilo Ortega. As noted previously it is located closer to the Pacific coast. Specifically, the coordinate location of Managua with respect to longitude and latitude is: 12°8′11″N 86°15′5″W. The latitude of 12° will be useful when understanding how to tilt the solar panels for maximum irradiance.

Nicaragua typically has two seasons, a season of rainfall (May – October) and one of dryer warmer climate (November – April). As a result of the extended periods of rainfall during the rainy season, the lowlands experience lower direct solar irradiance than the other season. There exist a few sources to analyze and view the irradiance patterns of regions over periods of time. To get an encompassing look at the climate and irradiance near Managua, resources maps which are a result of multiple organizations under the United Nations Environment Program (UNEP) was first examined. Figure 1.2 below is a sample of a few months of the year for solar irradiance in Nicaragua.

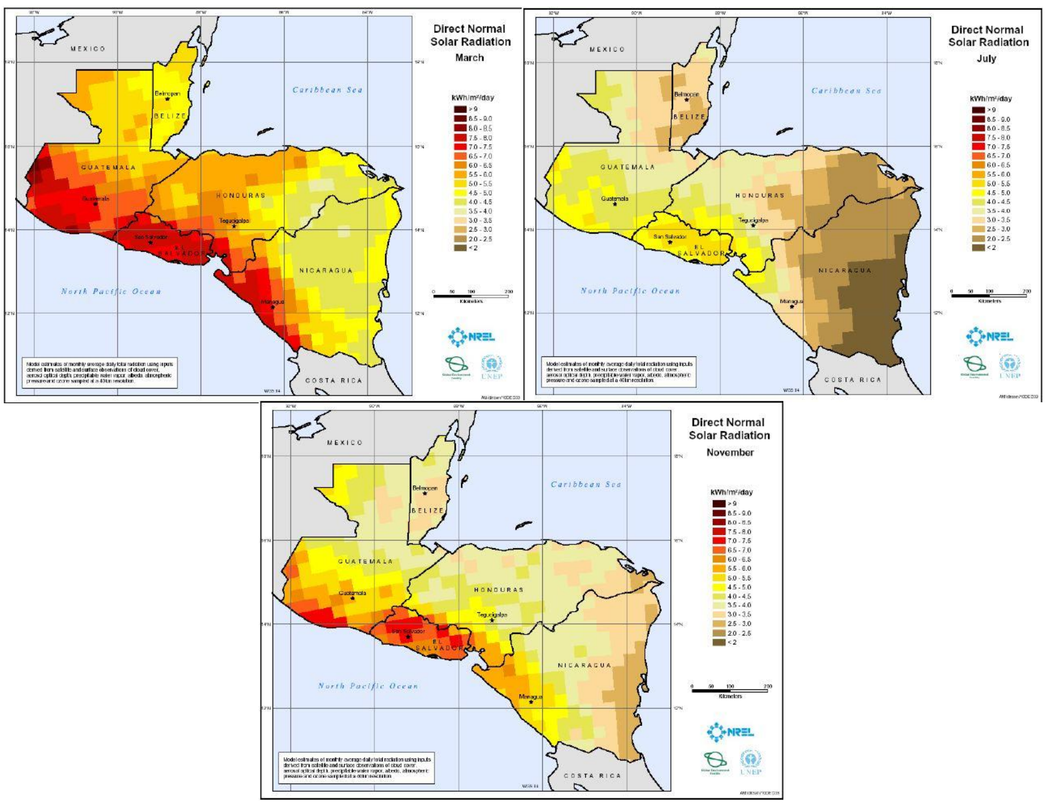


*Figure 3: March, July, and November Average Solar Irradiances[3]*

As Figure 3 shows, there can be some rather large shifts in direct solar irradiance based on the time of year. Overall, the general swing is from about 7kW/m$^2$ to about

3.0kW/m². For a more direct look, the SWERA Web Mapping tool was examined which is an interactive GIS tool for similar purposes of understanding solar viability. Using the Renewable Energy Explorer (RREX) tool, as seen in Figure 4, any point can be selected and general data can be gathered about the region. From Figure 5, an average annual Irradiance over the region can also be obtained.

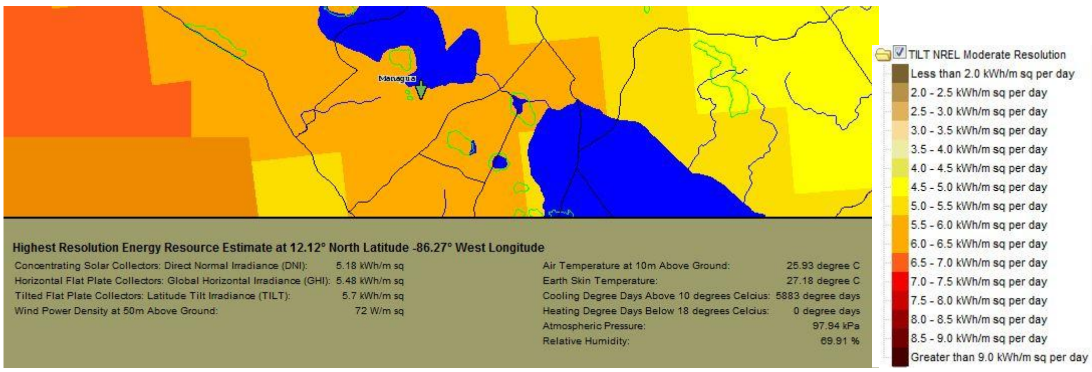


*Figure 4: SWERA Site Information and Associated Legend[4]*

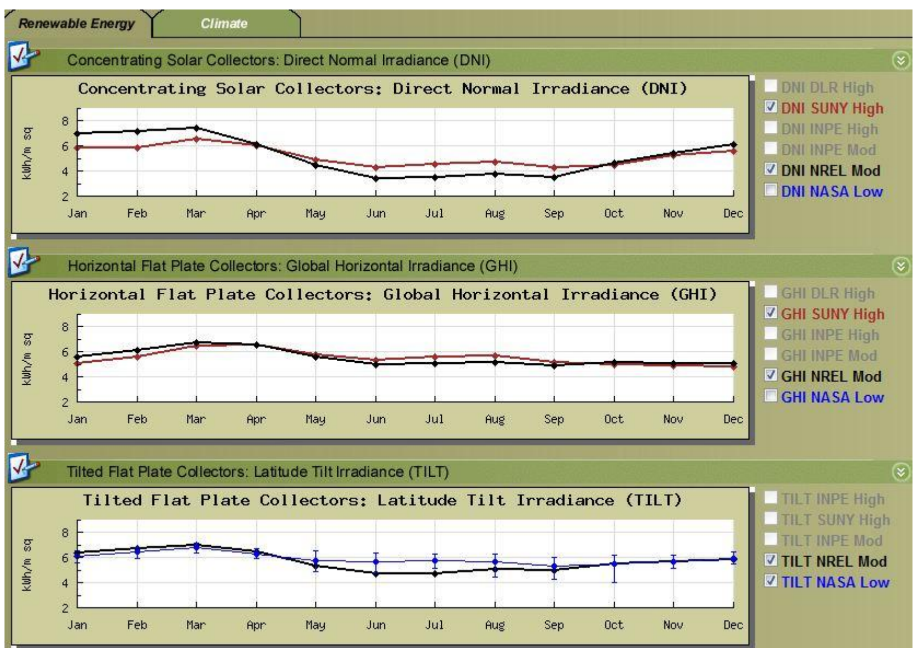


*Figure 5: SWERA Graphs of Averaged Irradiances at Tilt of Collector*

Both Figure 5 and Figure 3 have similar data results. These show the trends in irradiance as a result of the dry season and rain season. It is assumed that data for

Managua are relevant and appropriate for Camilo Ortega. It can be concluded, therefore, that during the peak irradiance months, the solar irradiance may swing from about 5.5kW/m$^2$ to about 7.5kW/m$^2$, whereas the low points swing from about 3kW/m$^2$ to about 5kW/m$^2$. This is necessary to know for the reason of sizing the photovoltaic array as there must be enough tilted collectors with enough irradiance upon them to generate the expected power for the load.

With this information a design team can now begin to design a photovoltaic system for these conditions. Given an average year-round temperature of about 75 degrees Fahrenheit[5] and latitude of 12 degrees a system can be optimized for peak performance.

## Expected Load Estimations

The first step to designing any stand-alone PV system is to first figure out what the PV system needs to supply. A PV array will need to be designed according to the expected load of the health clinic, so it is imperative to not only be precise in calculating the expected load, but to also be generous in estimation. Overestimating the load will not be a major issue; whereas, underestimating the load could be very problematic as the health clinic's equipment is necessary for the well-being of the local population. When estimating the load of the health clinic, we will have to take a list of all the necessary equipment required to maintain a functioning facility. Once these items are compiled, it will be up to us to find the most power and cost efficient equipment available to the location. With the specific equipment selected, we must estimate the daily usage for each item and multiply it by its maximum power consumption. With the total power per day calculated we will then factor in other issues such as the battery round trip efficiency and overall losses.

As stated before, the first step is to compile a list of necessary equipment. Luckily, we were able to speak with a representative of DC Power Systems, Joseph Marino, and Brady Dunklee from ATRAVES (the NGO), who could provide recommendation of loads. A list of all the important equipment is as follows:

- Lamp Tube Lights (for all the rooms of the building)
- Fans (AC units are power-hungry and inappropriate)

- Refrigerator/Freezer (for medical supplies and samples, not food, etc.)
- Centrifuge (for separating samples, such as blood)
- Autoclave (for sterilizing utensils in the clinic)
- Hotplate / Stirrer

The list is very basic, so some extra power output capacity will be added to designing of the PV array to allow for added equipment later on, and for more leeway to avoid underestimating the expected daily load and potentially having over-drained batteries. Another benefit, as seen later, would be due to low irradiance days. With the list of equipment done, the next step was to research the available products and compare them to one another for the most cost efficient and power efficient models.

Each item selected had to list the maximum power consumption per hour available and the maximum amp-hour demand per hour. In searching, top of the line items were avoided as those are expected to be more efficient and the NGO would not purchase brand new equipment. With these values, we can then estimate the amount of time the equipment would be on for the average day. This was a very hard task to accomplish due to our lack of background in the medical field. After some basic research into the equipment we could estimate the length of time each item would be used in a day. To ensure we overestimate, rather than underestimate the load, and a sizing sheet provided by Professor Agbo was used as a reference. The sheet recommended that the rated wattage be multiplied by an adjustment factor; the adjustment factor is a standard of 85% which is an estimation of the efficiency of the inverter as these loads will be powered by AC and not DC. With ample windows in the building, the lights for each room will only need to be run during low light times such as around dawn, and for emergencies during the night. An estimate of 4 hours per day per light was chosen. With about 18 light fixtures necessary to light the whole building, we can estimate the total power consumption of the lights to be as follows:

$$P_{light} = 18 \text{ Lights} * ((\text{Rated Wattage per Hour} / \text{Adjustment Factor}) * \text{Average Hour Use per Day}) = \text{Total Light Consumption} \qquad Eq(1)$$

$$= 18 * ((36 / .85) * 4) = 3049 \text{ W/Day}$$

The fans are very necessary for a few of the rooms in the building during the summer months. Even though their usage is only limited to the summer months the daily estimated wattage consumption still needs to be included to size the PV array for the highest power drawing months. The building will have a built-in ventilation system, thanks to the building design by the civil engineers in Engineers Without Borders. However, three fans seem to be a suitable number for the areas of the building with the least air flow and for additional cooling. The fans will be running the vast majority of the day, so an estimation of 6 hours use daily seems reasonable. The estimation for the daily power consumption is as follows:

$P_{fans}$ = 3 Fans * ((Rated Wattage per Hour / Adjustment Factor)
* Average Hour Use per Day) = Total Fan Consumption Eq(2)

= 3 * ((180 / .85) * 6) = 3812 W/Day

The refrigerator/freezer will be running all day every day, but it will only actually run for about 20 minutes on the hour. With this we can calculate it to run for about 7 hours a day to allow the compressor to maintain temperature. There will only be one of these in the health clinic. The estimate for the daily power consumption is as follows:

$P_{Fridge}$ = 1 Fridge * ((Rated Wattage per Hour / Adjustment Factor)
* Avg. Hour Use per Day) = Total Fridge Consumption Eq(3)

= 1 * ((500 / .85) * 7) = 4118 W/Day

Only one centrifuge will be in the building and the run time will be minimal for the item as it is only used to do a few things, like separate material in a blood sample, and even that only takes one to two minutes. We will estimate the daily usage at two hours, with this even being a large overestimation. The estimate for the daily power consumption is as follows:

$P_{Centri}$ = 1 Centrifuge * ((Rated Wattage per Hour / Adjustment Factor)
* Avg Hour Use per Day) = Total Cent. Consumption Eq(4)

= 1 * ((120 / .85) * 2) = 282 W/Day

The autoclave is the most power consuming item in the health clinic, as the heating element to sterilize utensils draws a large amount of wattage.

Fortunately, like the centrifuge, there will only be one device, and it should only be run a few times a day, so a daily usage of about two hours will suffice. The estimate for the daily power consumption is as follows:

$P_{Autoclave}$ = 1 Autoclave * ((Rated Wattage per Hour / Adjustment Factor)
* Avg. Hour Use per Day) = Total Auto. Consumption Eq(5)

= 1 * ((1350 / .85) * 2) = 3177 W/Day

The final device on our list is the hotplate/stirrer combination. Once again, the usage of the item will be limited, so the daily usage estimate of two hours is a conservative one. Only one of these items will be in the clinic. The estimate for the daily power consumption is as follows:

$P_{Hotplate}$ = 1 Combo* ((Rated Wattage per Hour / Adjustment Factor)
* Avg. Hour Use per Day) = Total Combo Consumption Eq(6)

= 1 * ((600 / .85) * 2) = 1412 W/Day

A summary of all the data values and items in the health clinic can be seen below in Table 3.

*Table III: Summary of Loads and Power Use*

| Component Name (#) | Rated Wattage | Adjustment Factor | Adjustment Wattage | Hours Per Day Use | Energy Per Day Use |
|---|---|---|---|---|---|
| Lamp Tube Lighting (18) | 648 | 0.85 | 762.4 | 4.0 | 3049.4 |
| Fans (3) | 540 | 0.85 | 635.3 | 6.0 | 3811.8 |
| Refrigerator/Freezer (1) | 500 | 0.85 | 588.2 | 7.0 | 4117.6 |
| Centrifuge (1) | 120 | 0.85 | 141.2 | 2.0 | 282.4 |
| Autoclave (1) | 1350 | 0.85 | 1588.2 | 2.0 | 3176.5 |
| Hotplate Stir Combo (1) | 600 | 0.85 | 705.9 | 2 | 1411.8 |

The final step is to add all these devices daily power consumption and add all their respective amp hour demands per day found in the equipment spec sheets. The total power demand per day results was **15850 Watt-Hours.**

Amp-Hour Per Day = (Total Energy Per Day Use)/(Batter Bus Voltage) Eq(7)

= 15850 Watt-Hours/Day /48V =330AH/Day

The total amp hour demand per day results was **330 AH/Day.**

To properly design a PV system for the health clinic, the total power demand per day is divided by the battery round-trip efficiency, as a certain amount of power is lost through the complete cycle between PV array to battery to load and back to battery. The total power demand per day is also divided by the standard battery round-trip efficiency of 80% so the power output we were looking for the PV array to support was a follows:

$P_{Array}$ = Total power demand per day / Batter round-trip eff. Eq(8)

= 15850 / .80 = 19812 W/Day

**Watts per day.**

With the estimation of the expected load for the health clinic completed, we can now move on to the next step of designing a PV array and battery array to supply this daily power demand.

## Photovoltaic Array Sizing

There are many steps to designing and implementing a successful PV system; however, the foundation of all PV systems is the PV array itself. These include, finding the correct PV module for the system, determining the correct amount of modules to install, calculating the cost of the array and determining its fiscal feasibility, where to install them, and how to install them.

The first step to finding the best PV module for the health clinic was finding local PV suppliers and determining the most adequate module available from their stock and catalog. The supplier, ECAMI, is a renewable energy business based in Managua, Nicaragua, selling solar PV, wind power and hydroelectric systems. This is the optimal supplier for the job, as Camilo Ortega is approximately 15 miles away from Managua. For the estimated large wattage usage per day for the health clinic, the PV module selected from ECAMI was the Kyocera KD250GX, a 205 watt solar module. This PV module is the standard multi-crystalline design, as it is the most cost efficient PV module available on the market. While the name of the PV module suggests that the output of the solar module is 205 watts, this is far from the case as many factors affect the output. Solar modules produce dc electricity. The dc output of solar modules is rated by manufacturers under Standard Test Conditions (STC). These are standard conditions by which factories can easily reproduce to rate the manufactured PV modules. STC conditions are: solar cell temp. = 25 °C; solar irradiance (intensity) = 1000 W/m2 (referred to as peak sunlight intensity, comparable to clear summer noon time intensity); and solar spectrum filtered by passing it through 1.5 Atmospheric Pressure. The real output is effected by many variables, such as by production tolerance, heat, dust, wiring, and ac conversion. The tolerance of a PV module is usually given by the manufacturer. In the case of the KD205GX, the tolerance is at +5W/-0W, which is relatively good for a panel.

Temperatures affect the PV modules wattage output negatively, lowering the wattage as temperature increases. This can be seen in the Figure 6 below. As temperature increases, I does increase; however, V decreases much more rapidly, and with the basic power equation, $P = I * V$, with one value shrinking more rapidly than the other increasing, a decreasing power output results.

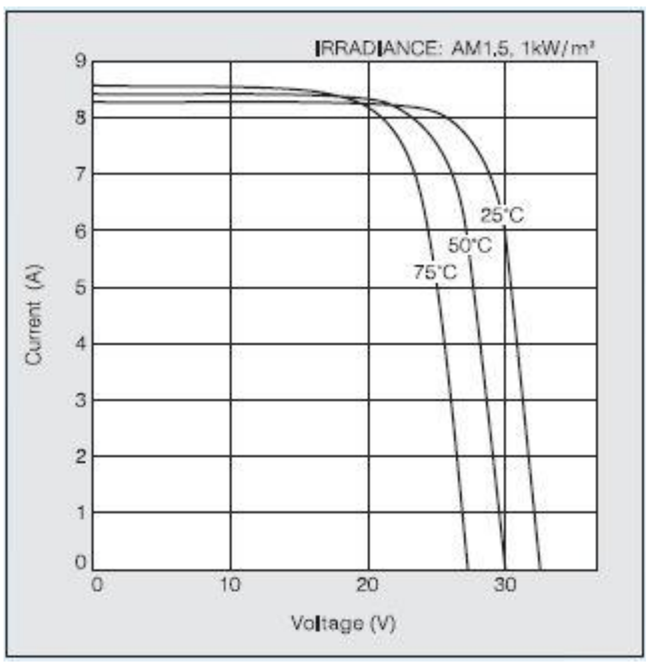


*Figure 6: I-V Characteristic for multiple temperatures of the Kyocera KD205*[6]

The issue of dust and dirt is more of an issue of proper care and maintenance of the PV array once it is installed. As Camilo Ortega is a rural area, the wind blowing up dust and debris is going to be an issue that will need to be addressed. The dirt and dust will accumulate on the PV module surface, blocking some of the sunlight from entering the cells, reducing the output of them. During the vast rainy season of Nicaragua, the solar panels should stay relatively clean (albeit resulting in less solar irradiance), but in the spring and summer, it is imperative that the community regularly clean the panels. If the panels are not cleaned, it is not uncommon for the PV array to lose anywhere from 5-7% of the total power output. Fundamental losses also occur from mismatching panels, and wiring. Mismatching panel losses are caused by the minute inconsistencies between connected modules, while wiring losses are simply unavoidable, but both can be kept to a minimum by carefully and correctly installing the panels and selecting the correct gauge of wire. The combined losses are around 3-5% loss to the total power output. The final major output loss comes in the form of dc-ac conversions. As previously stated, solar modules produce dc voltage, but all of the expected load in the health clinic will be ac voltage. The selected converter, which will be discussed in more depth later, has an efficiency rating of 93%, so that is a 7% loss on our total power output per module.

So after defining all this losses we can calculate our expected real life power output per module:

$P_{RealOut}$ = (205W * tolerance * fund. Losses * conversion eff) Eq(9)

= (130 * .95 * .97 * .93) ≈ **175 W**

Conveniently, this is the same value if we were to average the maximum power output with the power output of 80% irradiance. This value will be used as our selected PV module guaranteed power output.

Other factors necessary to determine the number of PV modules necessary to run the health clinics estimated expected loads are as follows:

- Selected PV Module Max Power Voltage (STC * .85)
- Peak Sun Hours at Design Tilt for Design Month
- Peak Sun Hours at Design Tilt for Worst Month
- Nominal Rated PV Module Output

The selected PV module maximum power voltage was determined by taking the PV module maximum power voltage found in the KD205 spec sheet multiplied by .85, which equaled 22.61V, but the spec sheet from Kyocera registers about 24V at 80% of max irradiance, which is the value we have chosen to use. The other three factors were determined in the local climate and weather section of the report. The table below was used to calculate the number of PV modules necessary to power the estimated loads of the health clinic.

*Table IV: PV Array Calculation Size*

| **Photovoltaic Array Sizing.** | Data | Units |
|---|---|---|
| Total Energy Demand Per Day | 15849.4 | Wh |
| Battery Round-Trip Efficiency (70%-85%) | 0.8 | |
| Required Array Output per Day | 19812 | Wh |
| Selected PV Module Max Power Voltage (STC * .85) | 24 | V |
| Selected PV Module Guaranteed Power Output | 175 | Watts |
| Peak Sun Hours at Design Tilt for Design Month | 6 | Hours |
| Energy Output Per Module Per Day | 1050 | Wh |
| Module Energy Output | 840 | Wh |
| Derating factor DF = .8 for hot climates. | | |
| Number of Modules to Meet Energy Requirement | 23.6 | Modules |
| Number of Modules Required Per String Rounded Up | 2.0 | Modules |
| Rounded Up | 2 | Module |
| Number of Strings in Parallel Rounded Up | 11.8 | Strings |
| Rounded Up | 12 | Strings |
| Number of Modules to be Purchased | 24.0 | Modules |
| Peak Watts of Array | 4200 | Watts |
| Peak Sun Hours at Design Tilt for Worst Month | 4 | Hours |
| Average Daily PV Energy During Worst Month | 10752 | Wh |
| Average Daily PV Amp-Hours Production - Worst Month | 224 | Ah |
| Nominal Rated PV Module Output | 205 | Watts |
| Nominal Rated Array Output | 4920 | Watts |

As Table 4 shows, the number of required PV modules calculated is 24. With the price given by the local supplier of $610.00 per module, the approximate the cost for the array is about $14,640 dollars.

The next step is determining where to install the PV array. From the spec sheet each PV module is approximately 59.1" x 39" or an area of 2305 square inches. Multiply this by 24 and the total area required for installation is calculated to be 55,318 sq. in or 4,610 square feet. For the ideal case, we would be able to fit all of the PV modules on the roof of the health clinic. This is the most ideal for two reasons, one being that the PV modules will be safe and out of the way from any accidental damage or tampering, and two being that the elevated height of the roof helps reduce any chances of power output losses due to shading from other objects. The PV array may be mounted above and parallel to the roof surface with a standoff of several inches for cooling purposes. A schematic of the health clinic to be built is shown below in Figure 7.

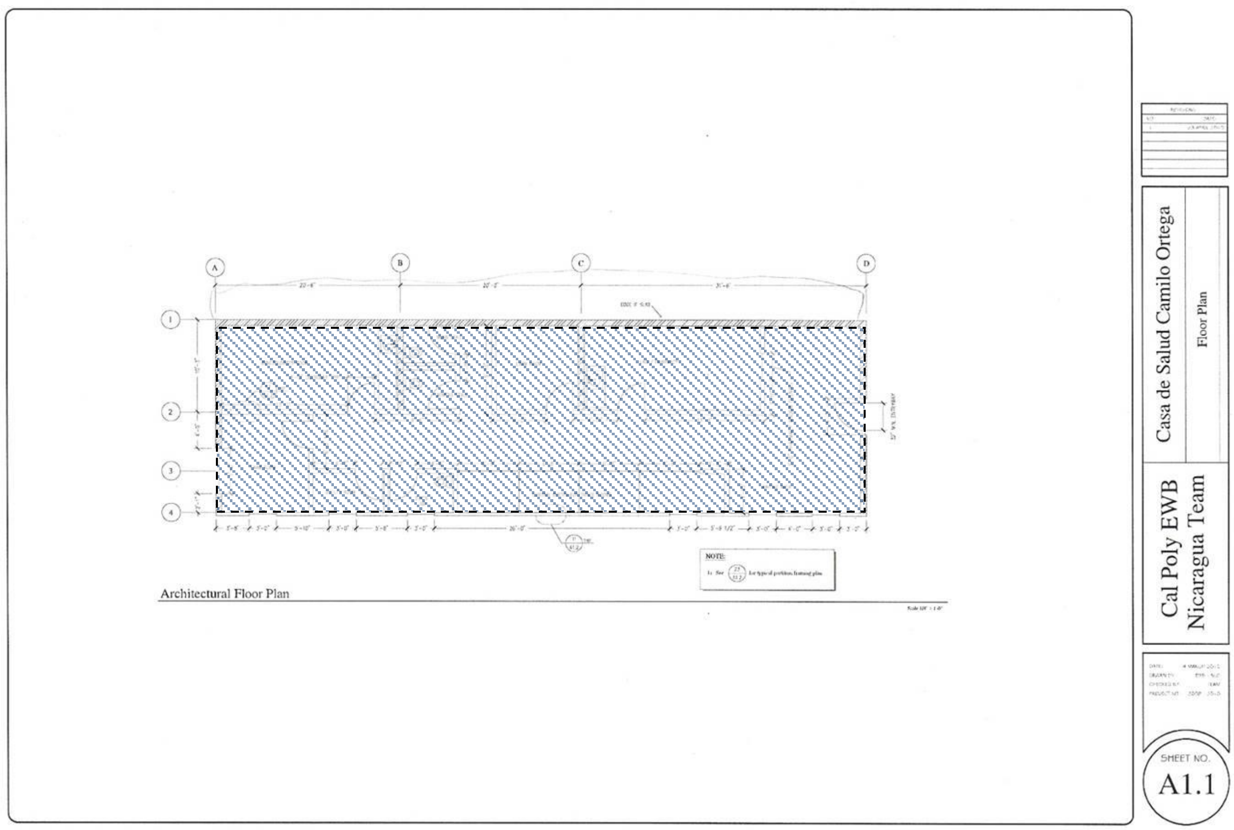


*Figure 7: Schematic of the Health Clinic in Camilo Ortega, Nicaragua*

The area highlighted in Figure 7 indicates the total area of the roof of the clinic, but it should be noted that the roof will actually be at a minor pitch. The area of this section of the roof can be calculated by its width 71.5' and length

10.5’, which is approximately 108108 sq. in. At first glance, it seems there is enough room on the roof to support installing all 24 modules; however, consideration should also be given for access to the system. This access space can add up to 20% of needed area to the mounting area required. So we subtract 20% of the 108108 sq. in. from the total roof space to get the actual available area on the roof for proper access space, which is 86486 sq. in. 86486 sq. in. > 64064 sq. in. So mounting all 24 PV modules on the roof is feasible!

Proper roof mounting can be very strenuous, but when planning a PV array on the roof of a new construction, as in the current case, the issue of removing and replacing roof materials is not an issue. The support brackets can be mounted after the roof system is applied and before the roofing materials, such as shingles, are installed. The crew in charge of constructing the PV array can install brackets for the modules in this time between roof decking and weather insulation. One bracket per module will be necessary to support the weight of the modules properly on the roof. Once the brackets for the PV modules are in place, the construction team can continue to cover the roof with the proper roofing material for weatherproofing, such as shingles.

In this section we have covered all the components that were necessary to design and build a stand-alone PV array for the health clinic in Camilo Ortega, Nicaragua. The next step in the PV system is the design and implementation of the battery array and backup generator.

## BATTERY SIZING

Batteries, in addition to the Photovoltaic array, are important components of any off-grid system. Without a battery bank loads would be able to operate during sunlight, and periods of enough sunlight at that. Batteries provide multiple days of autonomous power in the event of low irradiance or other similar event. Lead-acid batteries are the most common types of batteries for solar power systems but they are prone to frequent maintenance. Given limitless funds and an warehouse of infinite possibilities, lead-acid batteries, initially, would not be the selection of choice. However it it is necessary to remember that this design is also meant to not only be appropriate but also locally available. As a result, the team decided to stay with the lead-acid battery type. Because these batteries will receive charge and discharge on a regular basis, the team also need to find appropriate batteries which were also deep cycle. But most importantly, these batteries are going to be stored in a health clinic where women and children will be and medical professionals will conduct their activities and must be secured and safe. With this last requisite, the choice had to be clear. Of the various lead-acid batteries, there exists a variant known as valve-regulated lead-acid batteries which are commonly referred to as “sealed” batteries. Of this variant, there are, again, more choices, but the choice we made was the absorbent glass-mat (hereafter, AGM) battery. These batteries have the lead-acid electrolyte solution absorbed into fiber inside of the battery which reduces the likelihood of spills. After referring to ECAMI's brochure of available materials, the Ritar Power RA12-200D was selected. This has a bus voltage of 12V and a capacity of 200Ah. Using the data sheet, the proper sizing for the array can be seen below.

*Table V: Battery Array Sizing Sheet*

| Design Temperature: 72*F | | |
|---|---|---|
| Battery Sizing: | Data | Units |
| Daily Depth of Discharge Desired | 0.5 | |
| Allowable Dept of Discharge Limit | 0.8 | |
| Required Battery Capacity | 495 | Amp-Hours |
| Amp-hour Capacity of Selected Battery | 200 | Amp-Hours |
| Number of Batteries in Parallel | 2.48 | Batteries |
| Round Up: | 3 | Batteries |
| Number of Batteries in Series | 4.00 | Batteries |
| Round Up: | 4 | Batteries |
| Total Number of Batteries | 12.0 | Batteries |
| Total Battery Amp-hour Capacity | 600 | Amp-Hours |
| Total Battery Kilowatt-Hour Capacity | 28.8 | Kilowatt-Hours |
| Average Daily Depth of Discharge | 0.412745 | |
| Maximum Allowable Battery Charge Rate | 200.0 | Amps |
| Days of Storage | 1.453682 | Days |

As can be seen from Table 5, a total of 12 batteries will be used in this design. Each battery, unfortunately, weighs about 120lbs which is very heavy, but smaller batteries require more units at smaller capacities further increasing floor space. The 3 batteries in parallel will add an additional 105Amp-Hour to the desired design value of 495Amp-Hour, and the 4 batteries in series will combine their 12 volts to provide the desired input voltage to the inverter (48 volts). The results of this design provides about a day and a half of autonomous usage at full load (all loads being used for their specified time amounts). Of course, more is preferable but the cost is additional floor space and cost. We do not believe that the clinic would witness full load usage on a regular basis.

The cost of these Ritar batteries is $260.00 as priced by ECAMI, which results in a total cost of 12 Units x $260.00 = $3,120. This value is to be considered in the economic considerations later.

## Generator and Charger Sizing

This section presents the final sizing criteria for the photovoltaic hybrid system, the generator and charger sizing section. The ideal purpose of the generator is to charge the batteries when the depth of discharge is running too low or if the demand is high. The idea is to protect the batteries from too much discharge and provide power to the system in the event of low irradiance or power supply from the PV array. The wattage from the generator is meant to meet or exceed the total demand for the load so that, if necessary, it can provide it. Optimally, the generator would never have to run as the PV array could provide all the necessary power the loads need, but, again, the generator can be considered a countermeasure against low irradiance periods or periods of high clinic usage. The charger's sole purpose is to take the input from the generator and charge the batteries when necessary.

The generator and charger sizing can be seen below in Table 6.

*Table VI: Generator and Charger Sizing*

| | | |
|---|---|---|
| Choose Generator to Meet or Exceed Peak AC Demand | **All-Power America APG3009 Generator** | |
| Peak Generator Output | 6000 | Watts |
| Choose Battery Charger so that the maximum battery charger input AC watt is nearly equal but less than Peak Generator Output and the charger voltage is the same as the nominal battery voltage | **Magnum Energy** | **MS4448** |
| Battery Charger Maximum Charge Rate | 40 | Amps |
| Battery Charger Maximum AC Input Power | 5040 | Watts |
| Battery Charger Average AC Input Power | | Watts |
| Battery Charger Average DC Output Power | | Watts |
| | | |
| Generator Turn-On Point | 0.54 | |
| Average Daily Energy Deficit During Worst Month | 5097 | Wh |
| Average Daily PV Amp-Hour Deficit During Worst Month | 106.20 | Ah |
| Fraction of Battery Capacity Supplied to Battery From Generator/Battery Charger During Worst Month | 0.177 | |
| Generator Turn-Off Point | 0.764 | |
| Number of Months for which Peak Sun Hours per Day Design Tilt are Less than Design Month Peak Hours | 5 | |
| Required Number of Months for Which Generator/Battery Charger Backup is Required Daily | 5 | |
| Required Generator/Battery Charger Amp-Hour Production During Charging Cycle | 144.88945 | Ah |
| Average Yearly Generator/Battery Charger Amp-Hour Production | 22035.27 | Ah |
| Battery Charger Average Charge Rate | 40 | Amp |
| Average Generator/Battery Charger On-Time During Cycle (should not be less than 15 minutes) | 3.62 | Hours |
| Average Yearly Generator/Battery Charger On-Time | 550.88 | Hours |

It is important to note that the charger and inverter unit are one in the same. The unit itself charges from a generator (or other power supply unit) and also acts as an inverter from any battery or storage device it charges. The most important information to take from Table 6 is the Average Yearly Generator/Battery Charger On-Time value. This value indicates the number of hours the generator must run in one year, under expected loads, to supply enough power to the clinic when irradiance is low. The value as listed in Table 6 is 550.88 hours. Dividing this value by 24 hours will provide the number of days this generator would be expected to run in an average year; this value is 22.9 days. Ideally, the average on-time in hours would be 0 (indicating that all energy generated is through the photovoltaic array), but this is not the case. 22.9 days results in the generator running for 6.27% of the year. Keeping this value low will also increase the usable life of the generator itself. Diesel generators have high initial costs, require maintenance, and must be refilled with diesel fuel; the less the generator is used, the better. Fortunately, as stated in Table 6, the on-time for the generator as it recharges battery levels is only 3.62 hours. After actually using a diesel generator in Nicaragua during the construction of the clinic itself, it is apparent that the fuel is consumed by these units faster than expected and they are quite loud; during days of construction the rented generator was being run for 6 hours at a time, making the 3.62 hour run-time much nicer on the environment and ears of the community.

## System Design Analysis

As with any design project, it is important to fully test a project's layout and the design itself against practical application before being fully implemented. There are different sustainable and renewable energy groups which have developed software to test a planned implementation of photovoltaic systems. We came across two which were free: NREL's HOMER[7] and the University of Geneva's PVSYST[8] systems. The latter comes with a 15 day free trial, after which the user must purchase a license.

Through the use of both tools, each stood out as having distinctly different attributes. HOMER focused on, in addition to the technical aspects of the design, the cost, lifetime, and depreciation of the project as a whole.

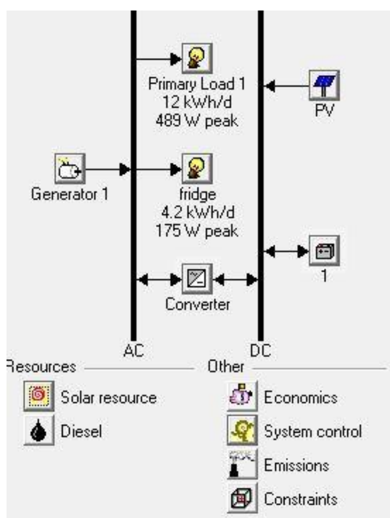


*Figure 8: Image of HOMER's System Set-Up UI*

As seen from Figure 8 above, it is useful to note the flexibility in HOMER's UI and the in-depth analysis that it can go into further for the more studious projects including emissions, economics, and (if a diesel generator is used as is in this design) the cost and implications of diesel use. However, after using both programs I found PVSYST to be much more user friendly and intuitive. As such, the analysis below has been done with the PVSYST program.

While the longitude and latitude of a location may provide a generalized and averaged aggregate of solar irradiance data, it is necessary to take into account other factors such as hills, trees and other objects of shading. To account for this, PVSYST allows the user to edit irradiance to the array based on the time of day. Figure 9 below shows an example of the kinds of interference the array may receive from the shading and pitch of the roof. Figure 10 below shows the PVSYST user-customized day-long irradiance pattern.

*Figure 9: Image of Nearly Completed Clinic Site*

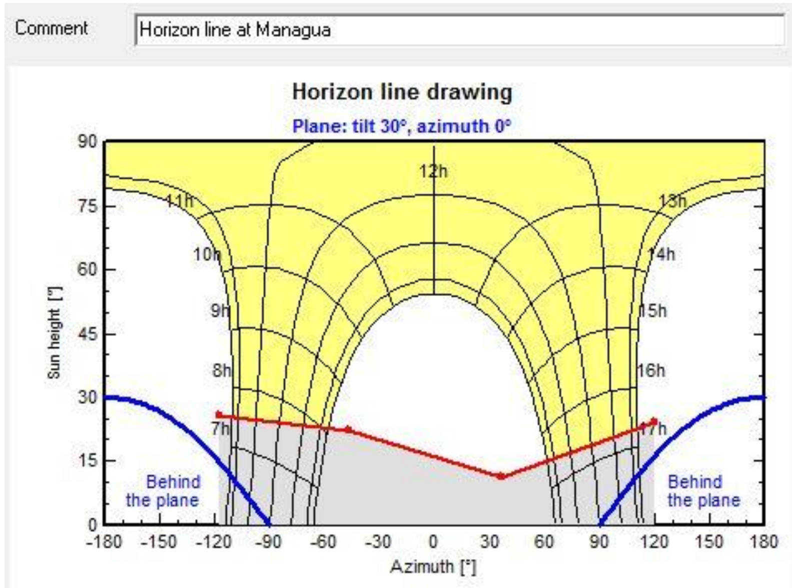


*Figure 10: Horizon Drawing for Clinic Array*

From this we then selected the type of panels and batteries used for the clinic to get the most accurate analysis possible.

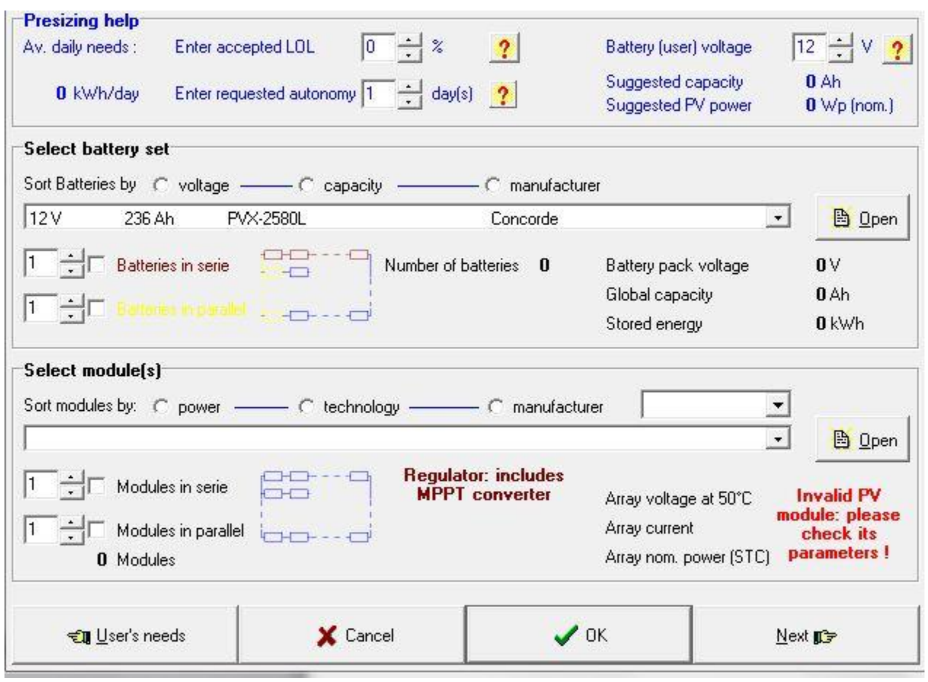


*Figure 11: Panel and Battery Selection/Specification Screen*

From Figure 11 above, it can be seen that the user can define additional factors like loss percentages and required days of autonomy. From these selections an analysis of the design could be made. Figures 12, 13, and 14 below show the results of this analysis featuring different losses and required days of autonomy combinations.

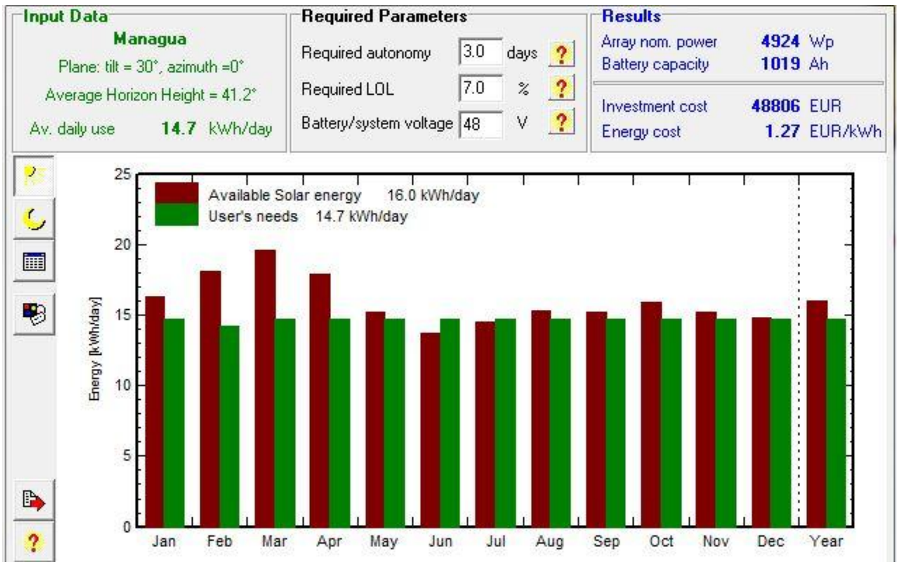


*Figure 12: PVSYST result for 3 days of autonomy and 7% losses*

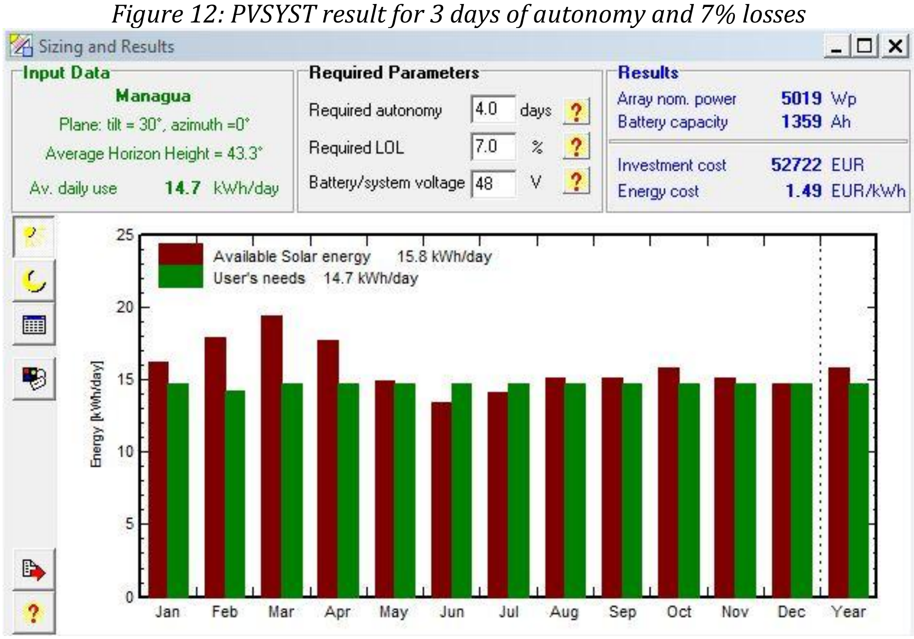


*Figure 13: PVSYST result for 4 days of autonomy and 7% losses*

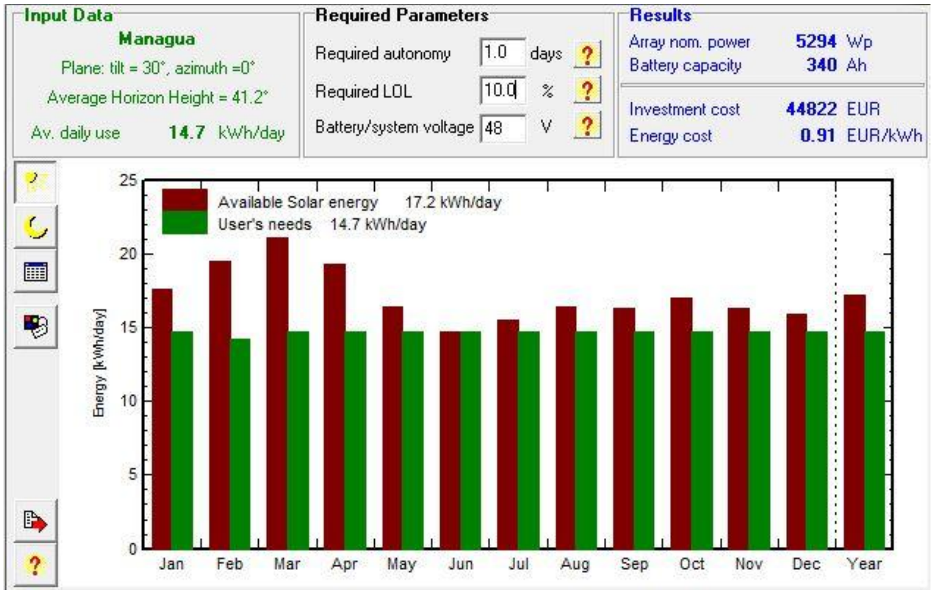


*Figure 14: PVSYST result for 1 day of autonomy and 10% losses*

Figure 14 displays the results which we believe to be the closest to the reality for the clinic array. This is because the NGO and our group do not expect to be under continual use for days and weeks at a time. Instead, for the first few months and years of operation the clinic use may very well be seasonal and sporadic through each quarter of the year. These gaps provide plenty of time for the batteries to charge while also providing power to the continuous loads such as the refrigerator.

PVSYST also provided a loss analysis to understand where possible shortfalls in power could be prevented. In Figure 15 below the large arrow from top to bottom shows where and what losses incur and to what extent they strip the load of possible power.

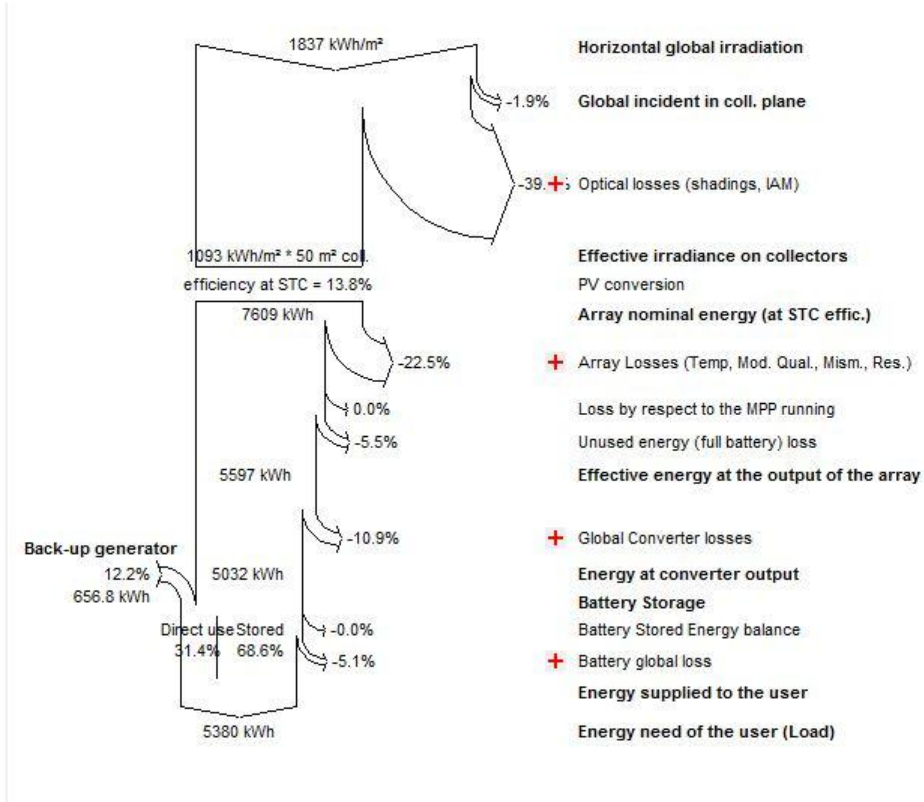


*Figure 15: PVSYST Loss Diagram*

It is evident that from the Loss Diagram that a majority of the total possible power generated is lost from shading and position of the tiles. Due to the slope of the hillside, the home on the plot above the clinic shades a large portion of the irradiance in the morning. The rest of the losses are incurred due to heat or inefficiencies.

## Economic and Cultural Considerations

In any design, cost reigns supreme and this design is no exception. The aim here is to keep costs low while also ensuring that the design meets the requirements of the project. In the case of this clinic, it is going to be run by the NGO ATRAVES which is also a non-profit organization, and a small one at that. This section will first discuss the total initial cost of the photovoltaic array, and then we will look at the cultural impact and perception of a photovoltaic array in the clinic, and finally come to a conclusion on ATRAVES' approval or disapproval of the design.

ECAMI has been the main source of photovoltaic-related information as it pertains to Nicaragua. However, it is not the only source for renewable energy products in the country; but ultimately, prices for the array were quoted from ECAMI as we used their stock and products. After a few discussions with Max Lacayo about budget, he provided us a quote for the installation that I've provided below in Table 7.

*Table VII: Quote provided by ECAMI for PV Array*

| | **SOLAR SYSTEM SEALED AGM BATTERIES** | | |
|---|---|---|---|
| 16 | Solar Panel KYOCERA KD205W 24VDC | 610.00 | 9,760.00 |
| 16 | Sealed Battery RITAR AGM 12VDC 200ah | 260.00 | 4,160.00 |
| 1 | Inverter/Charger MAGNUM ENERGY MS4448 4.4KW 110/220VAC | 1,717.00 | 1,717.00 |
| 2 | Charge Controller XANTREX C-40 amps 48VDC | 150.00 | 300.00 |
| 1 | Digital Volt meter XANTREX for C-SERIES | 85.00 | 85.00 |
| 1 | Labor & Electrical Materials | 0.00 | 0.00 |
| | | Sub-Total | 16,022.00 |
| | | IVA | 315.30 |
| | | TOTAL U$ | 16,337.30 |

As can be seen from Table 7 above, the overall cost of the PV array (excluding generator and the maintenance incurred therein) is $16,337.00. With these prices comes a guarantee that the panels will last 20 years, batteries will last 12 months, and the inverter and controller will last 2 years each. To purchase a generator would cost around $600.00 although the prices vary from retailer. The benefit to this design is that it can be, in effect, modular. The entire array and battery bank does not have to be purchased up front; it can grow as the electricity demand of the clinic itself grows.

Another important idea to consider is the cultural implications of this new technology being introduced. While renewable technology is not a foreign concept in Nicaragua, its exposure is not wide spread. That is to say, bringing photovoltaic panels into a community that is not used to nor has any idea what they are brings into question the efficacy of the design as a whole. To a more poor community like Camilo Ortega, the panels may be subject to theft or vandalism by thieves or gangs. ECAMI strives to teach the community and its leaders about the technology so that they may come to embrace it, but it only takes one or two people to ruin it.

Finally, the idea to implement this PV system fully rests on the approval of the project by the NGO. Not only must they consider initial costs but also the overall sustainability costs of the project over a multiple year period. After many discussions with Brady Dunklee, executive director and founder of ATRAVES, about the design and feasibility, he came to the conclusion that the photovoltaic array proposed here at its current cost and liability within the community would NOT be appropriate at this time; it was not a cost he could consider in this time of financial restraint. We were sent back to the drawing boards to consider alternatives to this design.

# Design Alternatives

This section will deal with primarily two alternatives to the photovoltaic array design with the focus of providing enough power for the clinic while maintaining a sense of the NGO's budget.

## Diesel Generators

During the 8/23/2010 – 9/14/2010 implementation trip with Engineers Without Borders to construct the health clinic wall shell and roof system, the team rented diesel generators to power to tools we required for ease of construction. Below is Figure 16 of the generator we rented.


*Figure 16: Diesel Generator Used During Construction*

This generator was used to power saws, vacuums, and drills and ran for periods of three to four hours. The generator had to be refilled every second or third day of use based on the power demands of the previous day. Below is a calculation of the conversion of

Nicaraguan cordobas to United States dollars along with a conversion from liters to gallons:

$$Price_{Fuel} = \frac{20.19\ cordobas}{liter} * \frac{1\ liter}{.26417\ gallon} * \frac{1\ dollar}{21.5\ cordobas} = 3.55 \frac{dollars}{gallon} \quad \text{Eq(10)}$$

As seen from the equation above, the price for fuel in Nicaragua is comparable to the price in the United States, while Nicaragua has a much lower standard of living. From this, it should be clear why any design should strive for the least generator use as possible to keep the cost of the fuel down.

In addition to fuel prices, the sound of the generator itself is unsettling. For much of the time we were using the generator, many members of the team opted to use earplugs when working with the tools simply for the sound the generator made. When the generator was on it could be heard up the path to the school and it is important to remember that many families live in the area with small children that play in the roads. One option to keeping the volume low would be to bring the generator inside the clinic itself, place it in the store room with adequate ventilation and safety precautions. However, as informed, it is important to keep vibrations to a minimum inside the clinic. Managua is already a seismically active region and a vibrating generator on the floor of the clinic could pose some unforeseen consequences to the structural integrity of the clinic itself.

To power the clinic solely off diesel generators would require multiple generators to provide sufficient power to keep a refrigerator running, multiple banks of lights, and whatever other equipment the NGO foresees using and, based on the load requirement, may require daily refueling. Keeping the generators outdoors would lead to vandalism, theft and increased wear due to weather.

For these reasons, using only diesel generators to power the clinic would be not only a detriment to the pocketbooks of the NGO and the emissions into the environment, but also to ears of the surrounding community.

## Grid-Connected Power with Battery Backup

The school that is right up the road from the clinic site is fed by the Nicaragua utility. Much of the surrounding utility taps into and pirates the power from the lines. After speaking with ATRAVES, they are now considering having the clinic connected to the utility.

One of the main problems with the electric utility is reliability. As an example, during the trip, we witnessed a power outage that was random and lasted one to two hours. When local community members and workers were asked if this was a frequent occurrence, they said that it was. While it would be wise to keep the clinic connected to the utility, it becomes essential to ensure there is a backup for if and when the power goes out.

The backup is necessary for the reason of critical loads. A local house may not have a need to have a backup system for when the power goes out but the clinic has critical equipment and medicine that may need to stay cool at all times. As discussed earlier in the expected loads discussion, an AC unit may be put it along with a refrigerator for medical supplies and medicine. A power outage that lasts for an unknown period of time could ruin and destroy the medicine or heat the room to an uncomfortable temperature. With the necessity of a backup system in mind, the alternative was set into motion. Luckily, it was fairly easy to transfer a couple items from the photovoltaic array design. Below in Figure 17, a black box-esque diagram outlines this alternative.

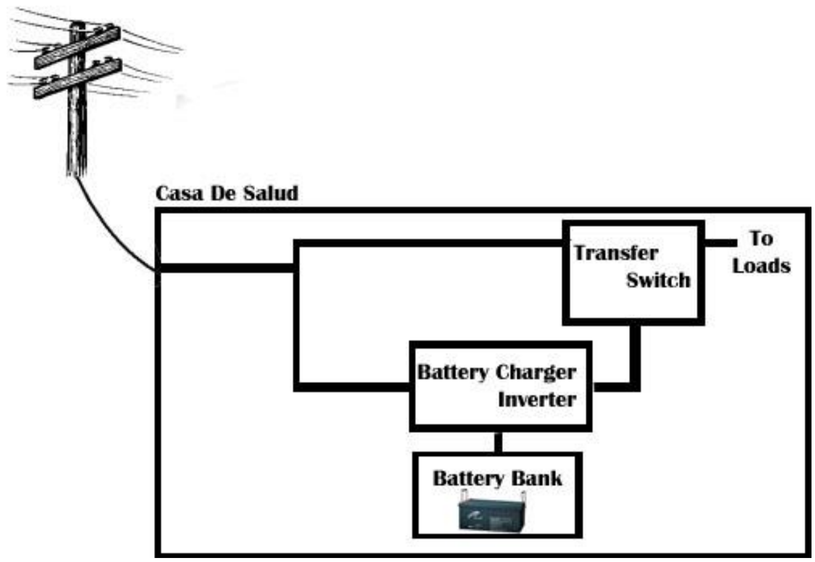


*Figure 17: Grid-Connected Backup System*

Using the same number of batteries from the photovoltaic array design and the battery charger and inverter unit this system provides a less costly, but effective alternative. In this case, the utility will be the main source of power. While the utility is on, the power from the utility will charge a bank of batteries. In the event of an outage, the transfer switch will switch to the battery backup and supply power to the clinic. When the main power is restored, the transfer switch will switch back to the utility power and resume powering the clinic as normal. As learned through discussion with Max Lacayo at ECAMI, the inverter and charging unit also acts like a transfer switch, eliminating the need for an additional piece of hardware that adds more to the cost.

The advantages of this design is that a majority—if not all—can actually be placed inside the clinic which can significantly reduce the susceptibility to vandalism and theft. Keeping these units indoors also prolongs the life as it reduces their exposure to the elements of the two seasons. The discussion of cost is also important, while the array may have been quoted at $16,337, this approach may cost less than half of that.

Furthermore, if ATRAVES ever intends to put solar panels on the roof in the future, some of their components will already have been purchased in this alternative.

As opposed to diesel generators, in this approach, the batteries can be sized and added on modularly to fit the clinic's needs if it were to grow or shrink. The batteries in the photovoltaic array approach were designed to provide a day and a half of autonomous power supply to the clinic. If desired this length can be scaled back to tailor the more appropriate outage length of hours and not days.

Having discussed this alternative with ATRAVES' Brady Dunklee, he was eager to hear that the price tag for this alternative was significantly lower than the previous estimate for the solar array. He had said that as the clinic prepares for electrification, they would further consider this option as a possibility for power. While it is still out of their price range for now, in the future, they agree it would be wise to invest into a backup system.

# WIRING THE CLINIC

During the previous Engineers Without Borders trip to the Camilo Ortega community in Nicaragua that occurred from August 24th, 2010 to September 14th, 2010 it was decided to layout the wiring diagram for the clinic. While we were working there was an electrician who was wiring the school. A meeting was requested with the technician with a translator nearby and Leticia Rojas the Nicaragua Executive Director for ATRAVES. With Ms. Rojas present at the meeting, we could better coordinate their desires for the clinic. Below is an image of our meeting with the electrician Juan.

*Figure 18: Juan and I discuss the electric layout*

During our discussion we discussed the kinds of loads the clinic would experience. Using the floor-plan we mapped out where the wiring would go including outlets, switches and the circuit breaker. We mapped the requirements of each room and decided whether the room would require 120V or 240V based on the advice of Ms.

Rojas. Juan also included his own recommendations for the wiring based on his own experience. The three images below are the section pieces of the floor-plan which have been drawn and edited by Juan and me.

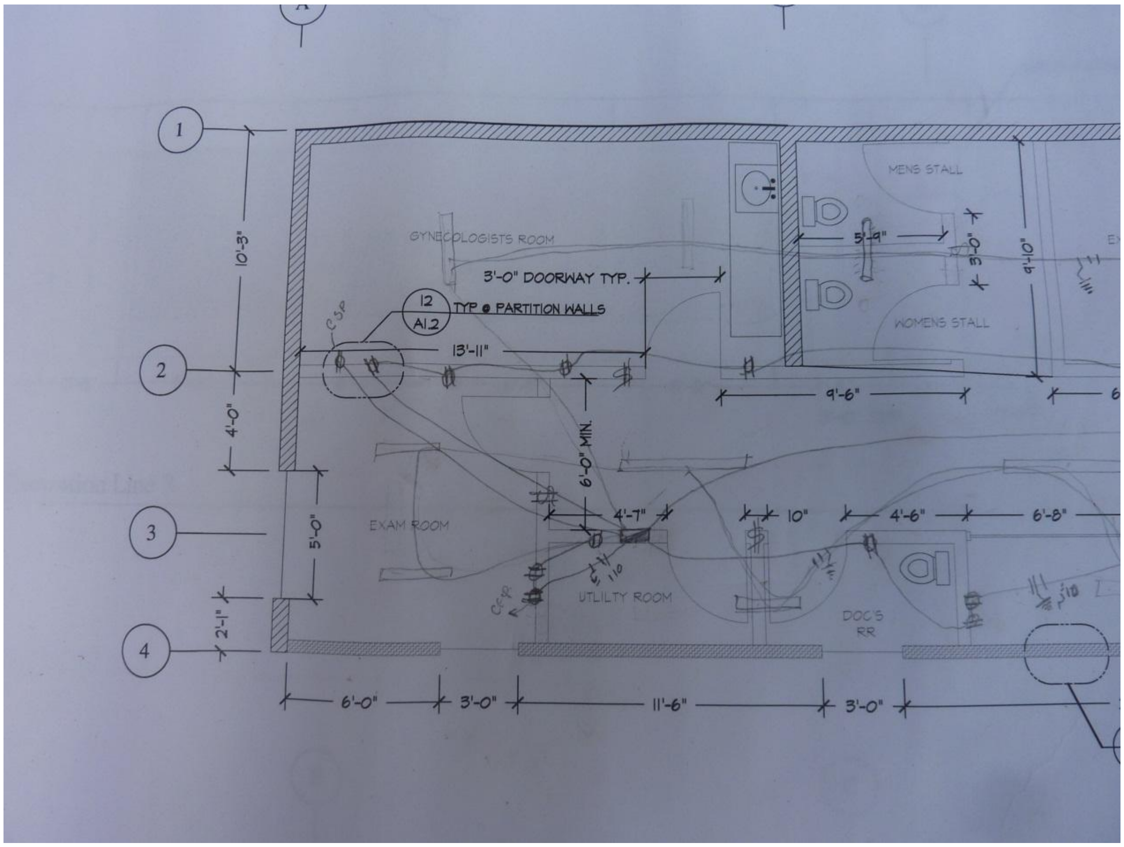


*Figure 19: Electrical Layout Pt. 1 (Left to Right)*

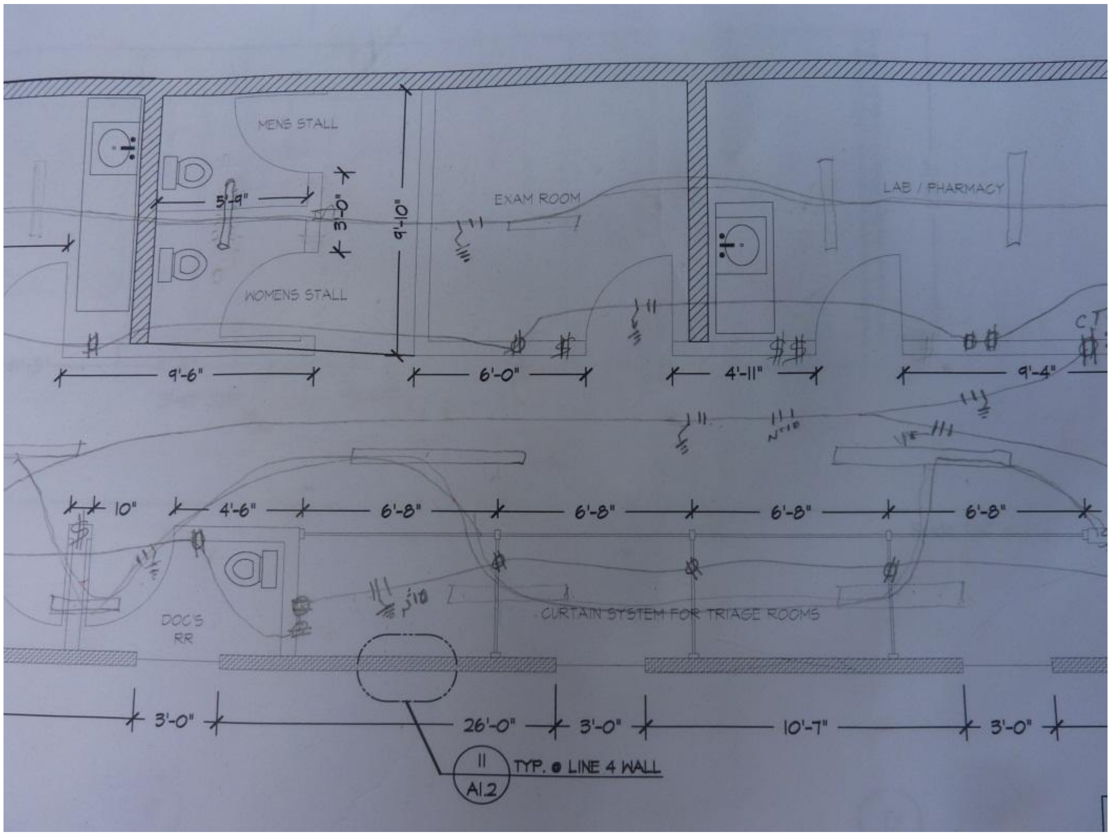


*Figure 20: Electrical Layout Pt. 2 (Left to Right)*

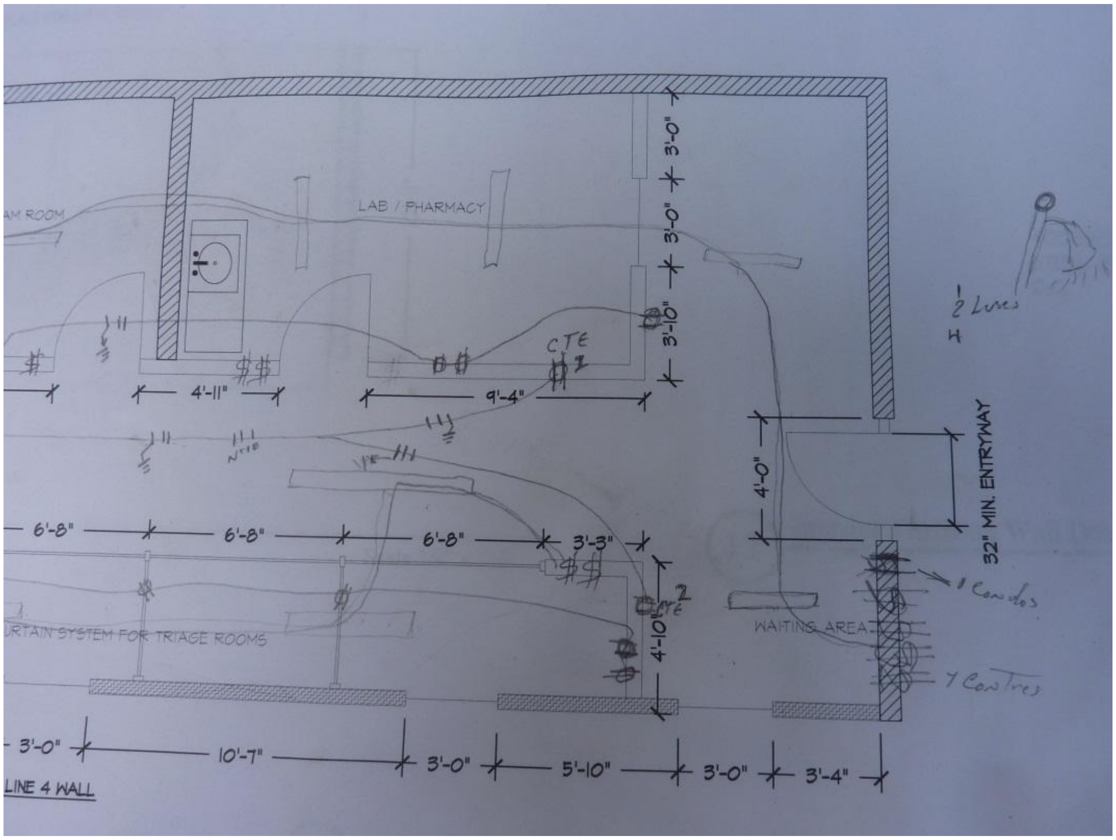

*Figure 21: Electrical Layout Pt. 3 (Left to Right)*

Table 8 below indicates the qualities of the 10 AWG wiring.

*Table VIII: Qualities of 10AWG Wiring[9]*

| AWG | Conductor Diameter (in) | Ohms per 1000 ft. | Maximum Amps for Chasis Wiring | Maximum Amps for Power Transmission |
|---|---|---|---|---|
| 10 | 0.1019 | 0.9989 | 55 | 15 |

Pictured below is an image of the wiring that Juan was using to wire the school; these wires appear to be 10 AWG.


*Figure 22: Wires that Juan Installed in the School*

Pictured below is the circuit break for the school.

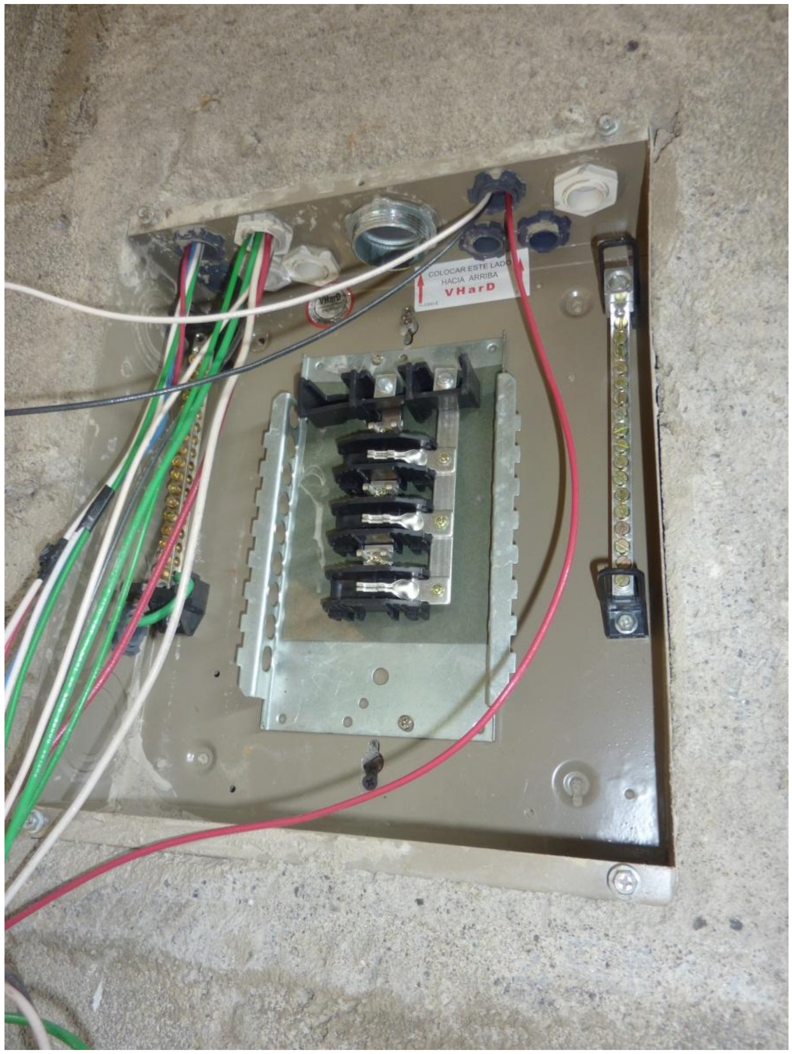


*Figure 23: A Circuit Breaker being Installed at the school*

Juan's expertise was instrumental to the completion of the wiring diagram as he was more knowledgeable about Nicaragua electrician trade.

Due to the fact that the clinic could not be fully completed during the trip, this was the extent of the electrical discussions with ATRAVES. Once the clinic is fully completed, ATRAVES, and Engineers Without Borders can have another discussion about the implementation of this plan.

# CONCLUSION

As the world's demand for electricity grows, rural areas in developing nations once without energy will soon have accesses to options that were inaccessible before. More importantly, where nations with established grids cling to old technology for power generation, the developing nations can assess a multitude of choices for their energy needs. Renewable energy is one area that continues to evolve and solidify its places as a viable option for power generation. While supranational organizations such as the U.N. enact policies to limit carbon emissions and curb global warming, these developing nations and the populations within can now make the decision to aid in this progression.

Engineers Without Borders is an international organization of multidisciplinary engineering students and professionals who work to bring sustainable and appropriate projects to developing communities. As a member and project manager of Cal Poly's Engineers Without Borders Nicaragua team, I have seen the projects and change that students have brought to communities worldwide; taking part in that change myself. I've met with a couple teams that brought electricity to rural villages in Africa through the use of photovoltaic arrays because transmission lines simply are not available. This project was spurred by those ideas, the drive to change lives, and the desire to inspire others to do the same.

This project's focus was to design a photovoltaic array for a clinic in Barrio Camilo Ortega outside the capital of Managua, Nicaragua. The community was settled as a refugee area composed, mainly, of women and children that have lived there since the revolution. When our Engineers Without Borders team came to the community and they requested a health clinic, we set to work on a design for one. As the only electrical engineer on the team I set out to design an alternative energy option which would provide enough energy to power the instruments and devices the clinic would require. I opted for a photovoltaic array because it was the most appropriate option among the renewable energy sources and the climate.

After discussing with ATRAVES the types of instruments and equipment they expected to house and use in the clinic, I set to find all the corresponding power ratings and average usage of each. I then proceeded to size the photovoltaic array based on the requirements set by the loads and also based on the stock and recommendations made by ECAMI. After sizing the array, analyzing it, and then understanding the costs I made the proposal to ATRAVES, but after serious consideration, they were unable to accept this as a viable option at this time.

I came up with two options: a diesel generator option and a grid-connected battery-backup system. The former choice was not viable after in-country use of a generator to power our tools. The generator was loud, intrusive, and required refilling of diesel fuel. It also adds to the carbon emissions and must be kept outside for proper ventilation; the result of which allows it to be susceptible to vandalism or theft. The second option is less vulnerable to theft, noiseless, requires less maintenance and can sustain a power outage. The core idea is that the grid would charge a bank of batteries while also powering the clinic itself. In the event of an outage, the inverter/charger internal transfer switch would then switch to the battery bank which would sustain power for the clinic up to a day or until grid power returned. This choice, between the two, is the best choice. ATRAVES stated their willingness to connect to the grid over the rather incredible expenditure to invest into a photovoltaic array.

During the previous trip to Nicaragua which involved the construction of the clinic shell and roof, I was able to meet with an electrician, Juan, who stated his willingness to provide his expertise with me in planning the wiring of the clinic.

Ultimately, I am hopeful that another student can pick up where I left off to implement this (or a better) plan for the clinic in Camilo Ortega and bring electricity to a community that truly needs it.

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